Beam Dynamics simulations in the CTF3 Delay Loop

LCWS 2014 - Belgrade - 08/10/2014

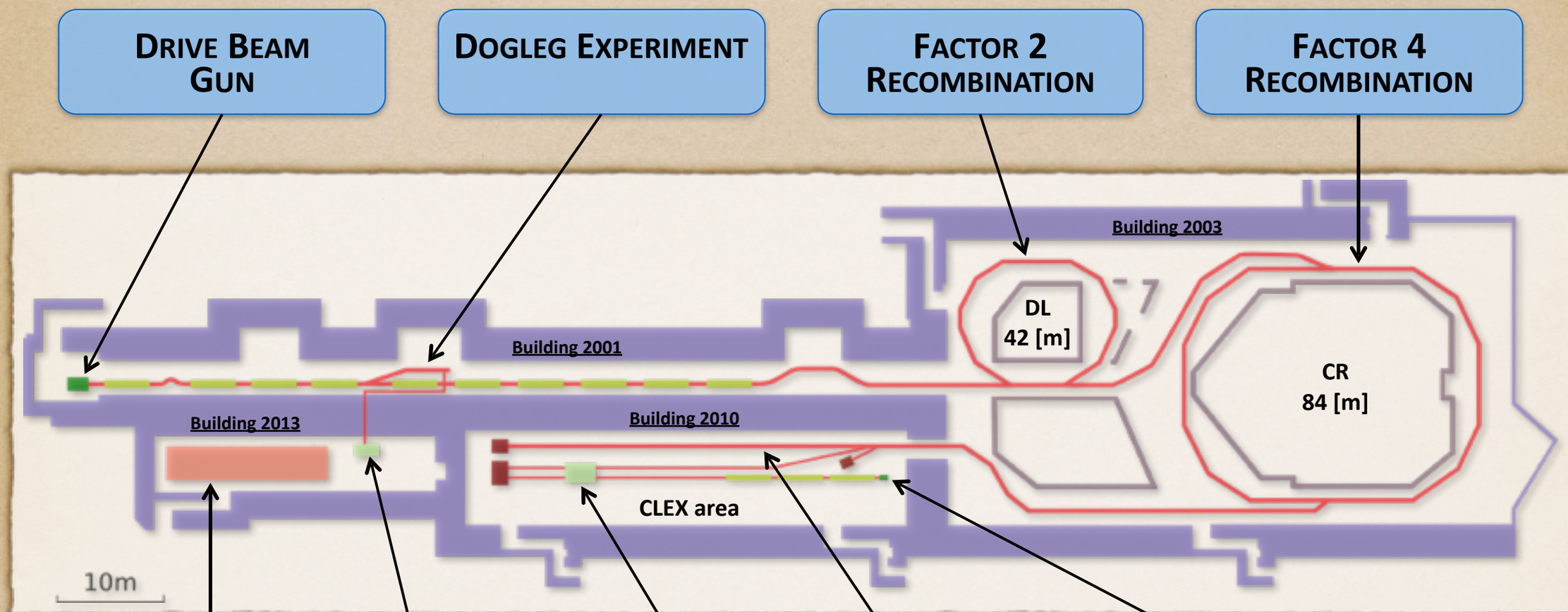
Davide Gamba

Outline

- CTF3 and its Delay Loop.
- Motivations.
- Simulations method.
- Beam description after one turn in Delay Loop.
  - Comparison with traditional tracking.
- “Emittance” along the Delay Loop:
  - Dispersion and Chromatic effects.
- An experimental test:
  - Implementing sextupolar correction.
- Conclusions.

davide.gamba@cern.ch

CTF3 - The CLIC Test Facility



Drive Beam Gun

Dogleg Experiment

Factor 2 Recombination

Factor 4 Recombination

Photo Injector Tests

Two Beam Test Stand (TBTS)

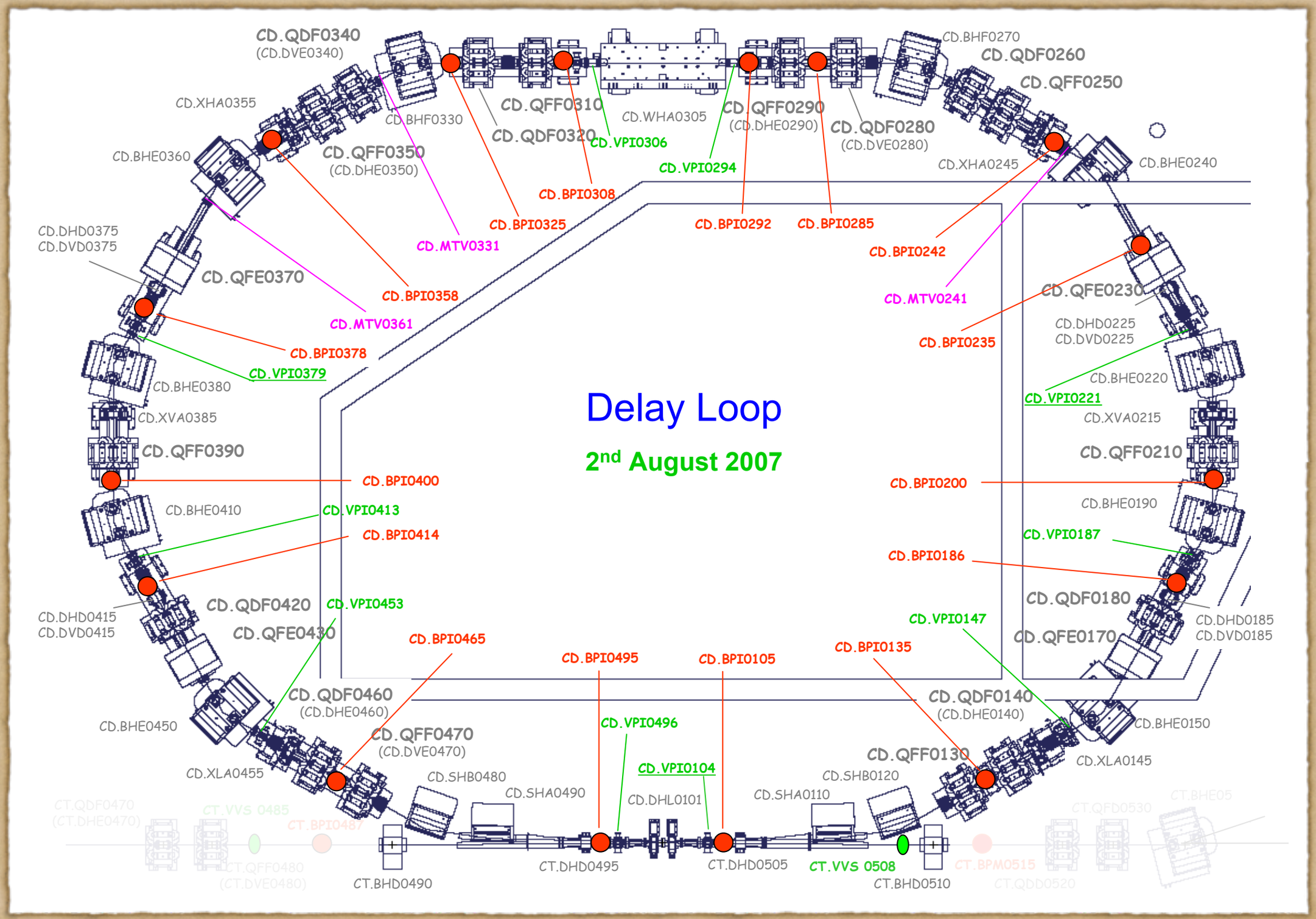
Probe Beam Photo-Injector

XBOX experiment

Deceleration Test Beam Line (TBL)

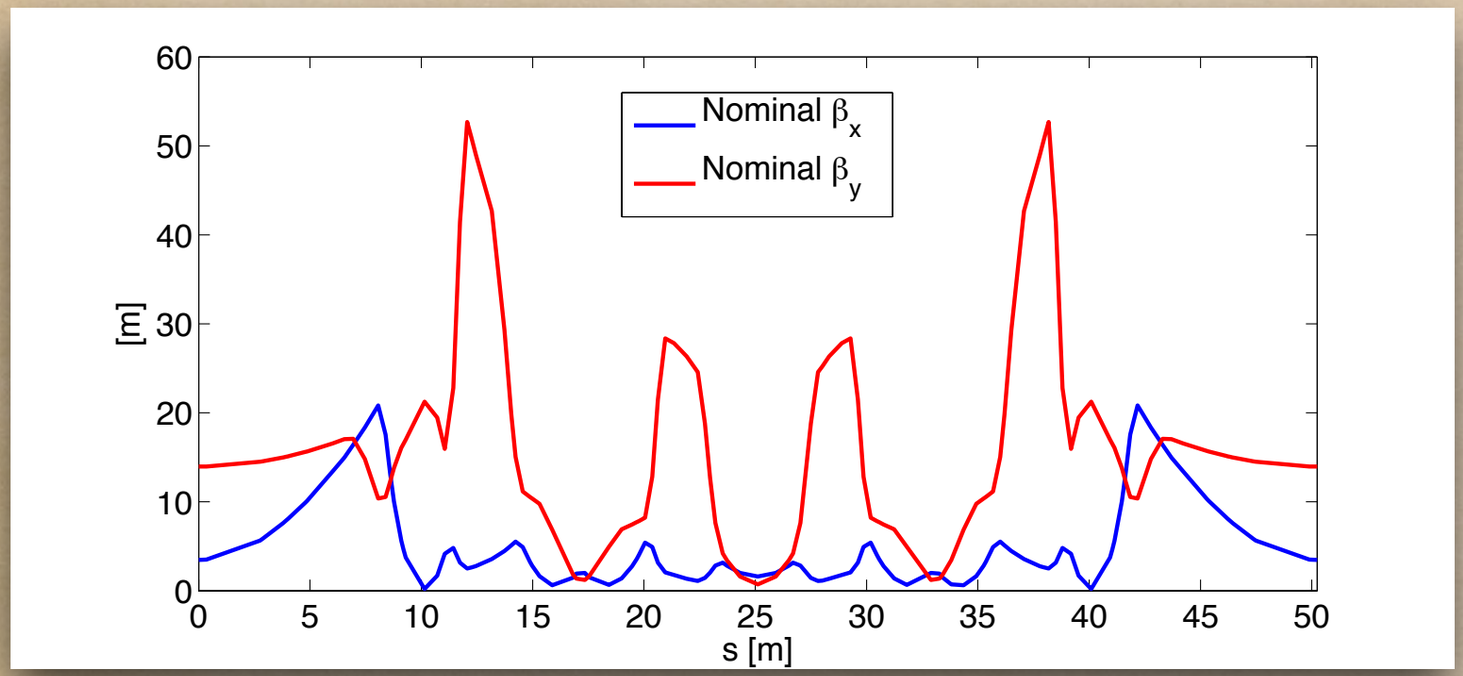
davide.gamba@cern.ch

CTF3 - The Delay Loop

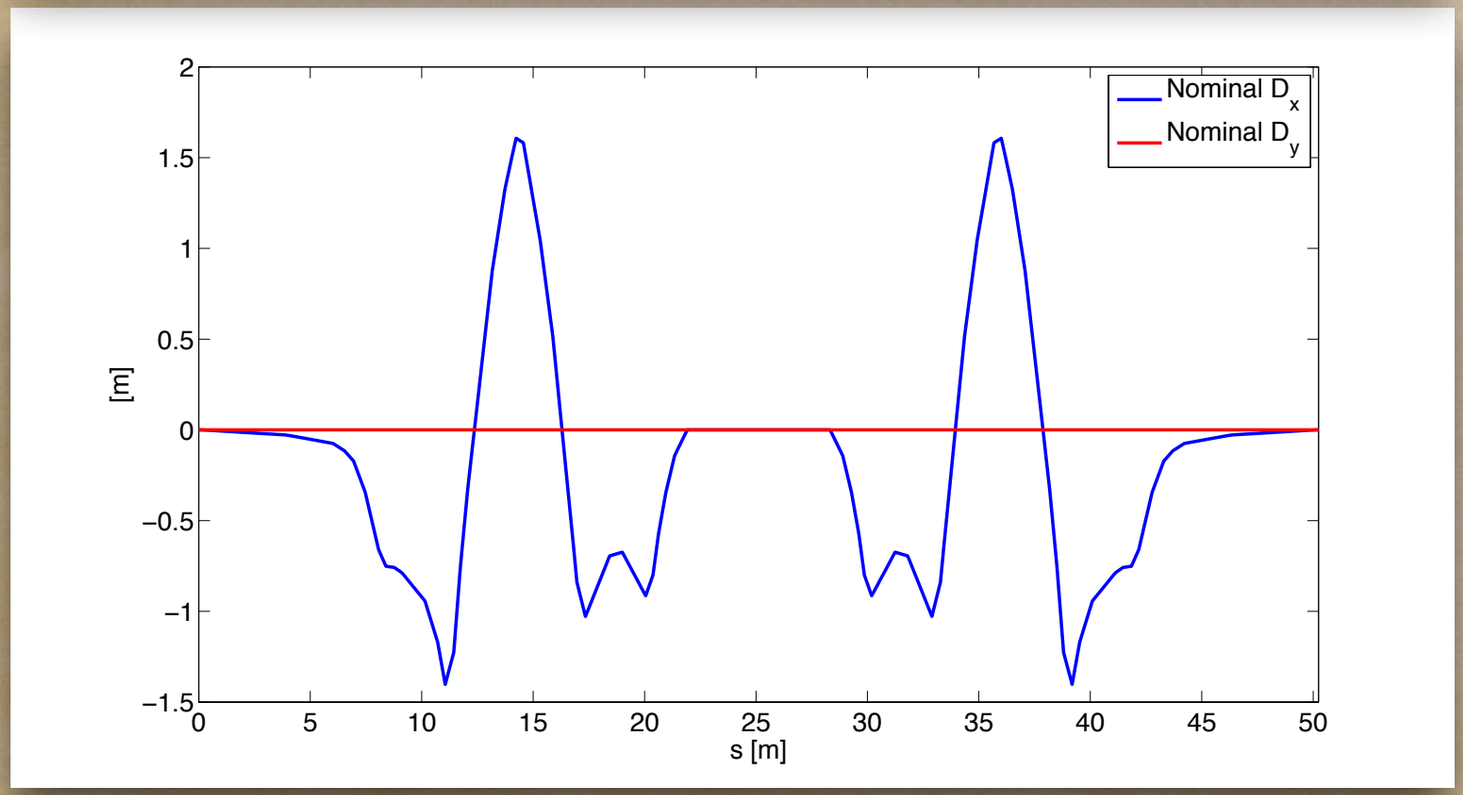


davide.gamba@cern.ch

Nominal optics of the Delay Loop



- Symmetric: the two half-arcs are powered in series.

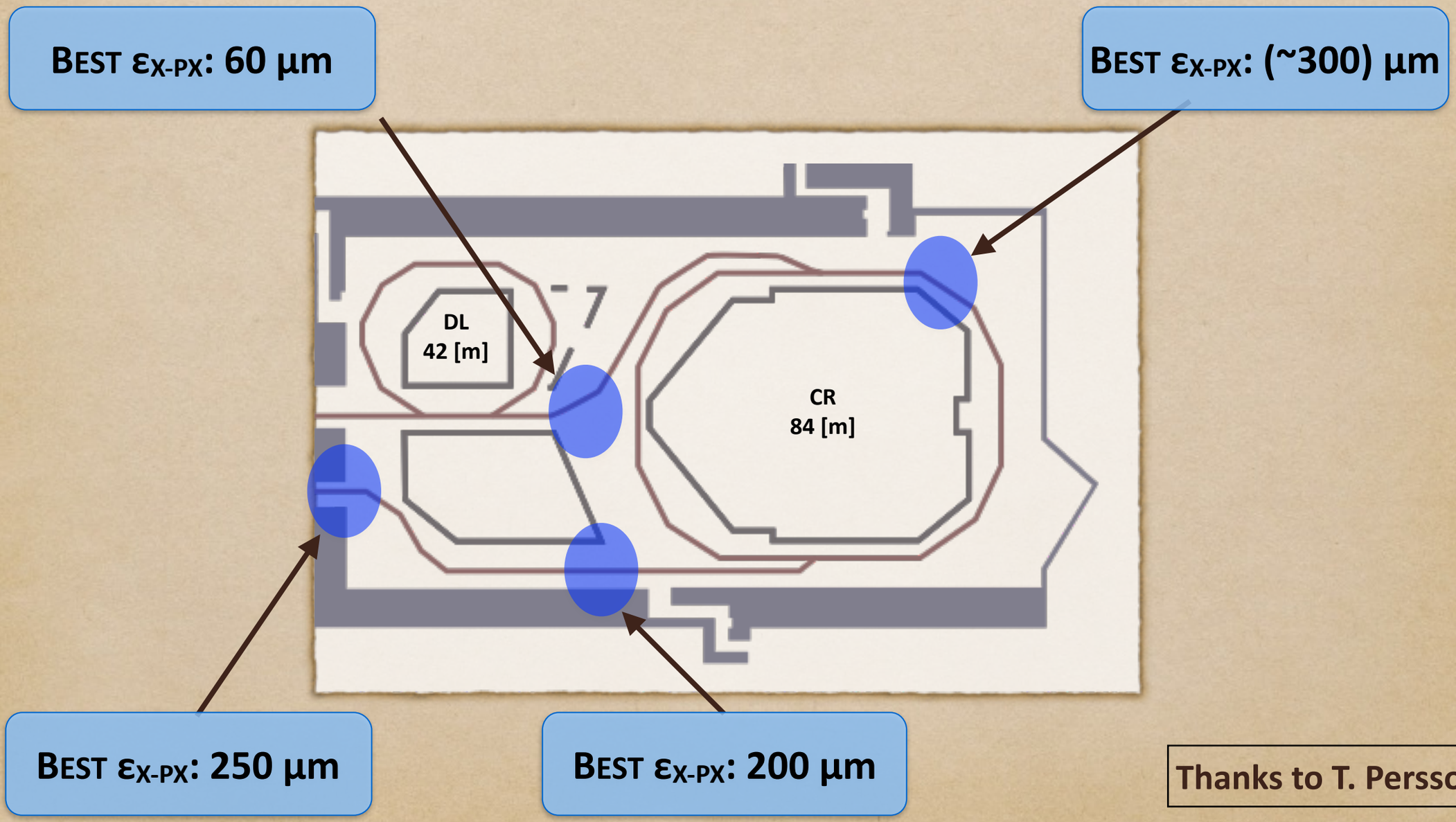


- Only Horizontal dispersion.
- Dispersion is corrected outside such that also R56 is 0 for total map.

davide.gamba@cern.ch

Motivations for the simulations

- Experimentally we see an increase of the measured emittance along the Drive Beam Recombination Complex.
- It might some optics problems, but also a measurement related issue.



Thanks to T. Persson

davide.gamba@cern.ch

Simulation method

- Final goal: simulate and identify the main sources of emittance growth.
- We simulate a **linear transfer line**:
  - mainly only dipoles and quadrupoles elements;
  - for a monochromatic beam sextupoles can be seen as quadrupoles with strength orbit-dependent.
- Non-linear behaviour hypothesised to be only given by energy spread:
  - **Magnetic elements** responses are in general **non-linear over Δp/p**.
- Trying to **avoid doing particle tracking**:
  - At the beginning the beam is a gaussian distribution of many monochromatic beams with different momentum;
  - all these beams have the same initial optical parameters and emittances;
  - **emittance of a monochromatic beam is preserved**;
  - real beam seen as composition of the different single monochromatic beams.

davide.gamba@cern.ch

Simulation method: few details.

- Particle tracking (linear approximation) looks like:

$$\text{beam} := \begin{bmatrix} \mathbf{x} \\ \mathbf{px} \\ \mathbf{y} \\ \mathbf{py} \\ \vdots \end{bmatrix} = \begin{bmatrix} x_1 & x_2 & \cdots & x_n \\ px_1 & px_2 & \cdots & px_n \\ y_1 & y_2 & \cdots & y_n \\ py_1 & py_2 & \cdots & py_n \\ \vdots & \vdots & \vdots & \vdots \end{bmatrix} \quad \Rightarrow \quad \begin{bmatrix} \mathbf{x} \\ \mathbf{px} \\ \mathbf{y} \\ \mathbf{py} \\ \vdots \end{bmatrix}_S = \mathbf{R_{0S}} \begin{bmatrix} \mathbf{x} \\ \mathbf{px} \\ \mathbf{y} \\ \mathbf{py} \\ \vdots \end{bmatrix}_0$$

- Beam envelope propagation looks like:

$$\Sigma = cov\,(\text{beam}) = \begin{bmatrix} \sigma(\mathbf{x},\mathbf{x}) & \sigma(\mathbf{x},\mathbf{px}) & \sigma(\mathbf{x},\mathbf{y}) & \sigma(\mathbf{x},\mathbf{py}) & \cdots \\ \sigma(\mathbf{px},\mathbf{x}) & \sigma(\mathbf{px},\mathbf{px}) & \sigma(\mathbf{px},\mathbf{y}) & \sigma(\mathbf{px},\mathbf{py}) & \cdots \\ \sigma(\mathbf{y},\mathbf{x}) & \sigma(\mathbf{y},\mathbf{px}) & \sigma(\mathbf{y},\mathbf{y}) & \sigma(\mathbf{y},\mathbf{py}) & \cdots \\ \sigma(\mathbf{py},\mathbf{x}) & \sigma(\mathbf{py},\mathbf{px}) & \sigma(\mathbf{py},\mathbf{y}) & \sigma(\mathbf{py},\mathbf{py}) & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \quad \Rightarrow \quad \Sigma_S = \mathbf{R_{0S}}\,\Sigma_0\,\mathbf{R_{0S}^T}$$

- "Emittance" is preserved along the line:

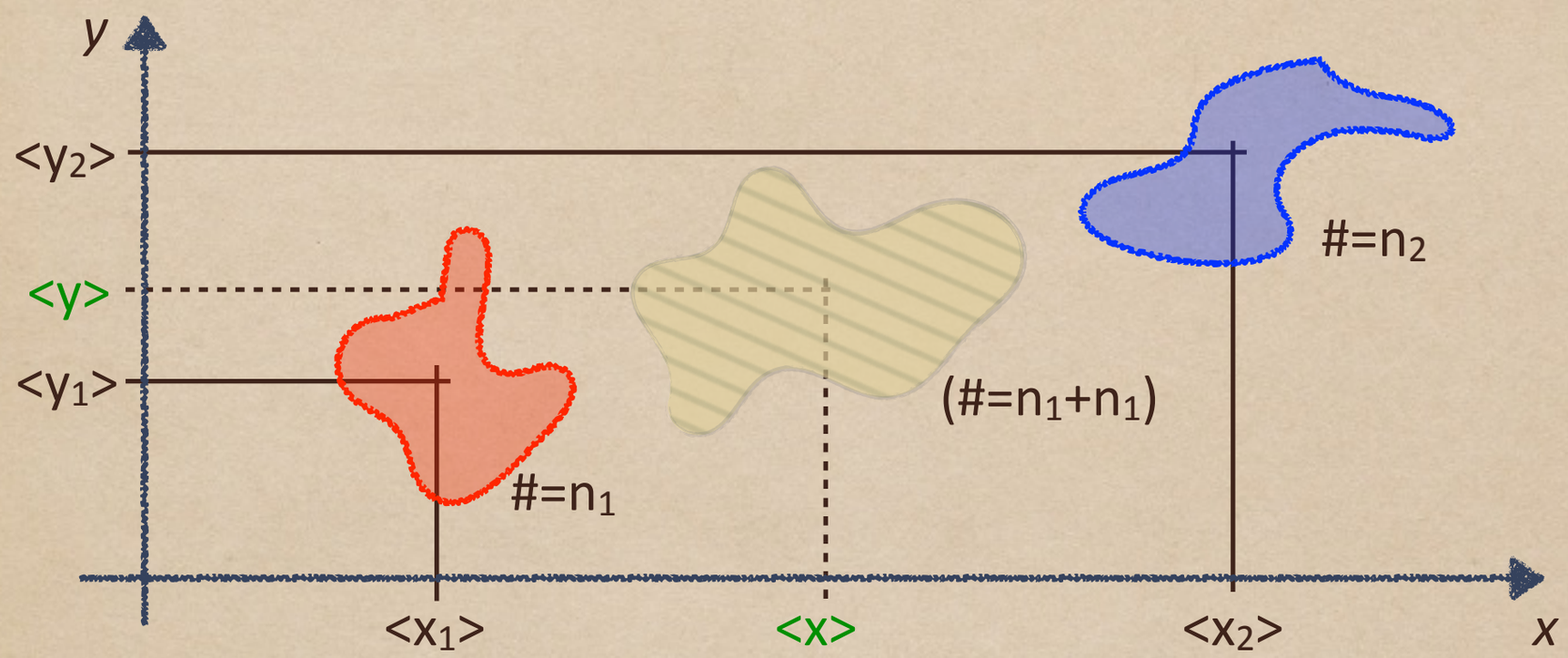
$$\det(\Sigma_S) = \det(\mathbf{R_{0S}}\,\Sigma_0\,\mathbf{R_{0S}^T}) = \det(\mathbf{R_{0S}})^2 \det(\Sigma_0)$$

=1 from symplecticity

davide.gamba@cern.ch

Simulation method: few details.

- Combine covariance matrices at one location:



$$\Sigma_1 = \begin{bmatrix} \sigma(\mathbf{x_1},\mathbf{x_1}) & \sigma(\mathbf{x_1},\mathbf{y_1}) \\ \sigma(\mathbf{y_1},\mathbf{x_1}) & \sigma(\mathbf{y_1},\mathbf{y_1}) \end{bmatrix}$$

$$\Sigma_2 = \begin{bmatrix} \sigma(\mathbf{x_2},\mathbf{x_2}) & \sigma(\mathbf{x_2},\mathbf{y_2}) \\ \sigma(\mathbf{y_2},\mathbf{x_2}) & \sigma(\mathbf{y_2},\mathbf{y_2}) \end{bmatrix}$$

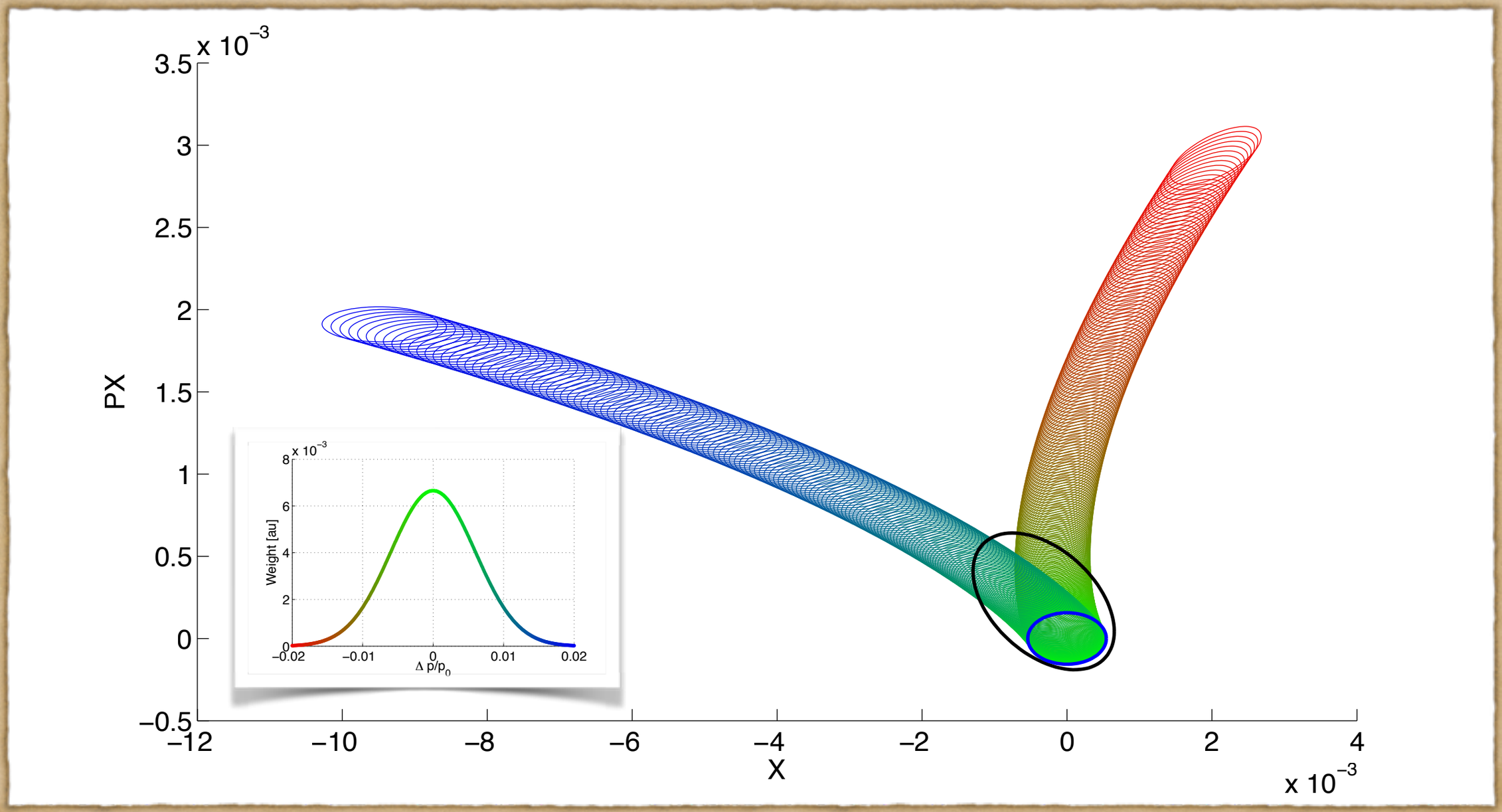
$$\left.\begin{aligned}
\sigma(\mathbf{x_1},\mathbf{y_1}) &= \langle \mathbf{x_1}\mathbf{y_1}\rangle - \langle \mathbf{x_1}\rangle\langle \mathbf{y_1}\rangle \\
\sigma(\mathbf{x_2},\mathbf{y_2}) &= \langle \mathbf{x_2}\mathbf{y_2}\rangle - \langle \mathbf{x_2}\rangle\langle \mathbf{y_2}\rangle \\
\sigma(\mathbf{x},\mathbf{y}) &= \langle \mathbf{xy}\rangle - \langle \mathbf{x}\rangle\langle \mathbf{y}\rangle \\
\langle \mathbf{x}\rangle &= \frac{n_1\langle \mathbf{x_1}\rangle + n_2\langle \mathbf{x_2}\rangle}{n_1+n_2} \\
\langle \mathbf{y}\rangle &= \frac{n_1\langle \mathbf{y_1}\rangle + n_2\langle \mathbf{y_2}\rangle}{n_1+n_2} \\
\langle \mathbf{xy}\rangle &= \frac{n_1\left(\sigma(\mathbf{x_1},\mathbf{y_1}) + \langle \mathbf{x_1}\rangle\langle \mathbf{y_1}\rangle\right) + n_2\left(\sigma(\mathbf{x_2},\mathbf{y_2}) + \langle \mathbf{x_2}\rangle\langle \mathbf{y_2}\rangle\right)}{n_1+n_2}
\end{aligned}\right\} \Sigma = \begin{bmatrix} \sigma(\mathbf{x},\mathbf{x}) & \sigma(\mathbf{x},\mathbf{y}) \\ \sigma(\mathbf{y},\mathbf{x}) & \sigma(\mathbf{y},\mathbf{y}) \end{bmatrix}$$

davide.gamba@cern.ch

Single passage in the DL: final ellipses

Executing 401 TWISS in MAD-X specifying different initial DELTAP values: from -2 to 2 %:

- Initial Beta/Alpha values as the closed solution (central blue ellipse).
- Monochromatic-emmitance of each ellipse assumed 60 µm (normalised).
- Black is the equivalent beam ellipse assuming Gaussian energy spread of 0.6%.

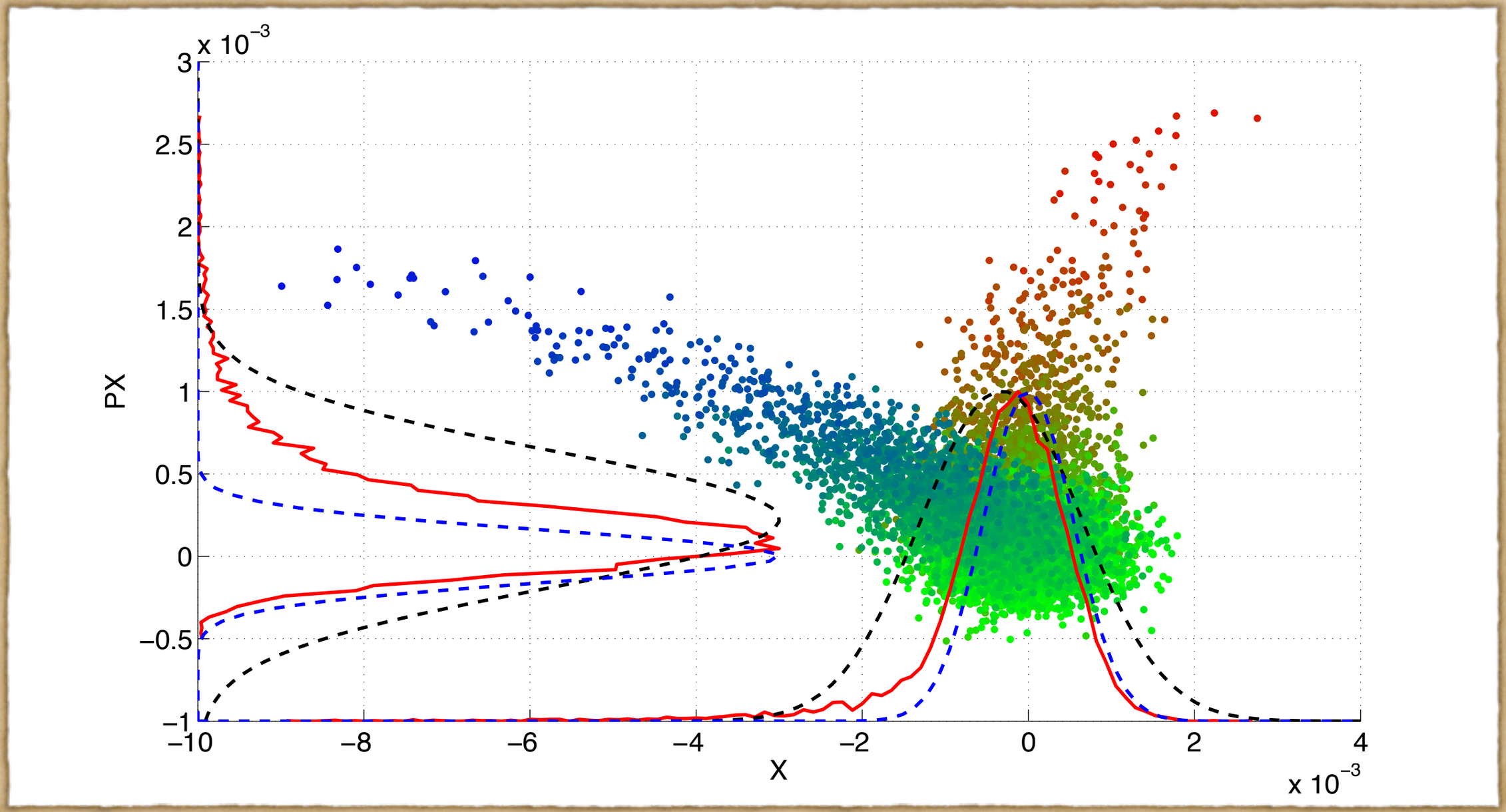


davide.gamba@cern.ch

In-place generated particles

One can populate each ellipse with locally-generated particles, properly weighted.

- Clearly there are only few particles with extreme energies.
- Projected profiles (red) are NOT gaussian as the nominal (blue)
- Gaussian profile with equivalent σ are much wider (black).

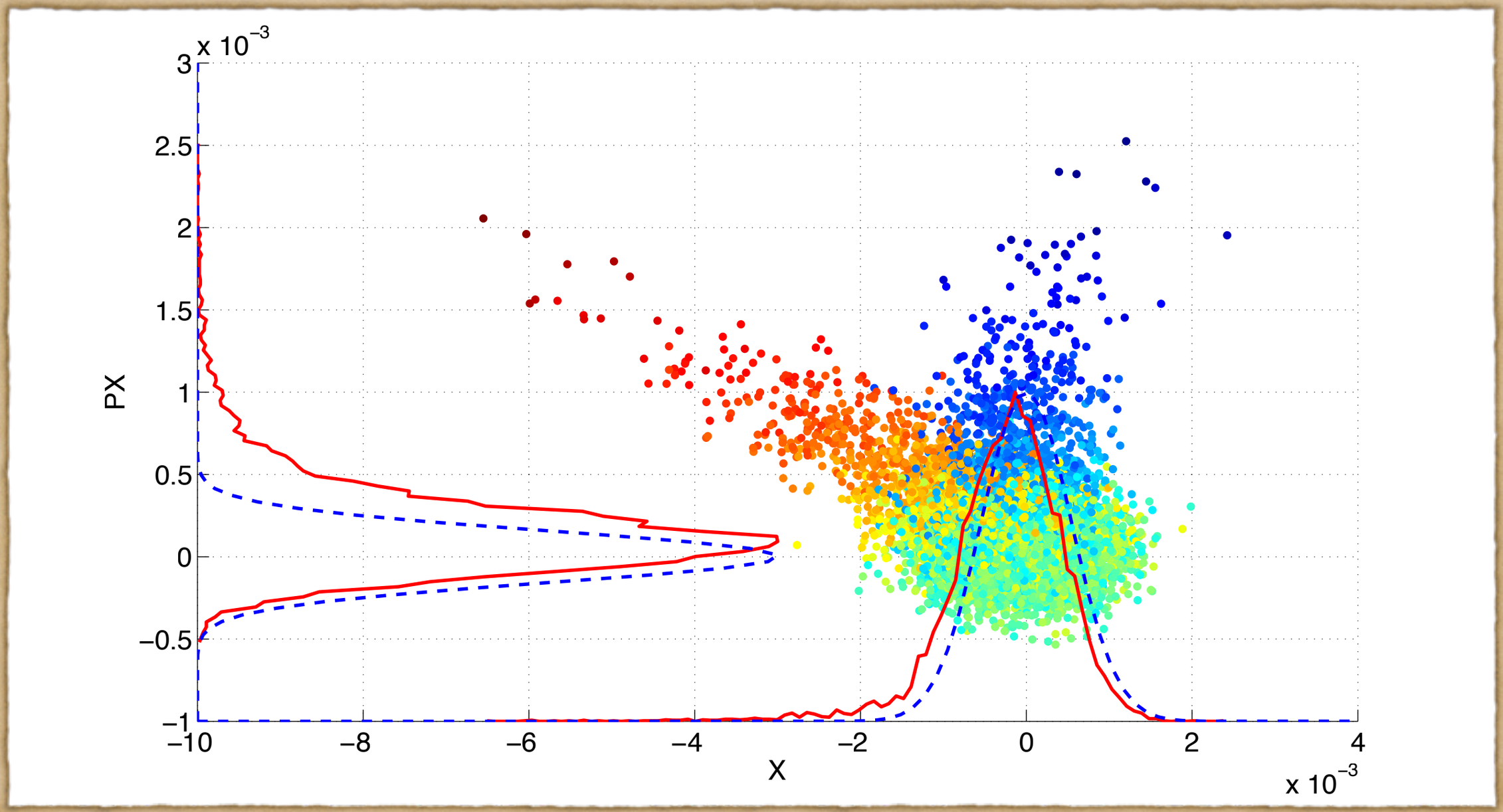


davide.gamba@cern.ch

Particle Tracking using PTC-TRACK

Same plot, but generating particles at the beginning of the Delay Loop and then track them with PTC-TRACK module (10.000 particles).

- It looks like we were a bit overestimating the effect.

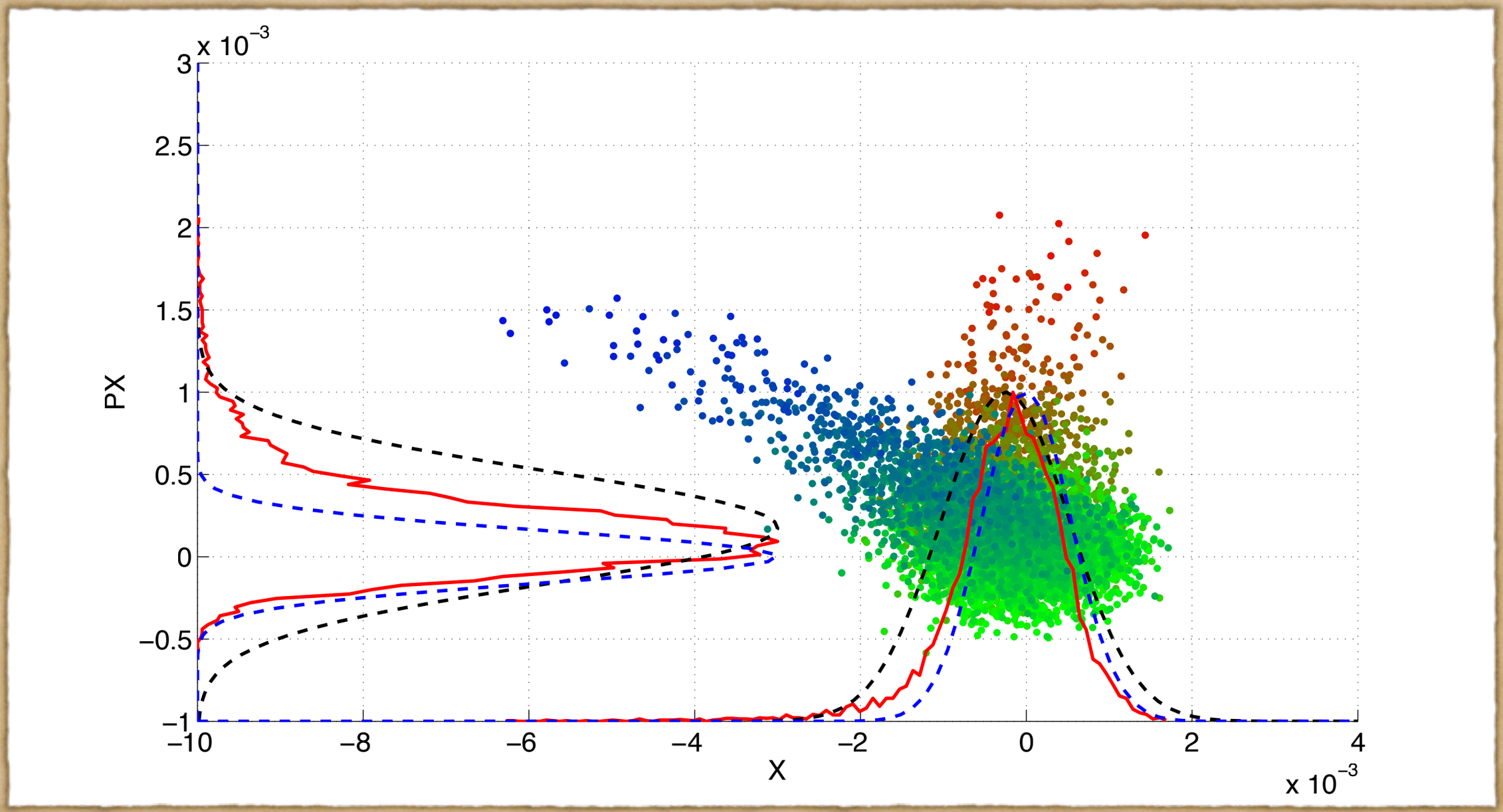


davide.gamba@cern.ch

In-place generated particles (study using PT instead of DELTAP)

Repeating the same method, but using different initial PT values instead of DELTAP for the MAD-X TWISS.

- More similar result to the PTC-Tracking.



davide.gamba@cern.ch

Numerical comparison

	ε	FWHM	FWHM
Nominal case	**60**	**1.28**	**0.37**
PTC-TRACK particles	(144)	~1.26	~0.4
Simulated equivalent ellipse	(257)	2.29	0.98
Locally-generated particles	(257)	~1.41	~0.45
Simulated(PT) equivalent ellipse	(167)	1.83	0.8
Locally-generated(PT) particles	(167)	~1.28	~0.43

- Emittance calculated as ε = sqrt(det(Σ)).
  - **! is the quantity that would be preserved if linear transport afterwards.**
- Locally generated particles with “PT-simulations” looks very closed to the PTC-tracking (but it can be anything).
- Difficult to have a single number representative of the beam size.

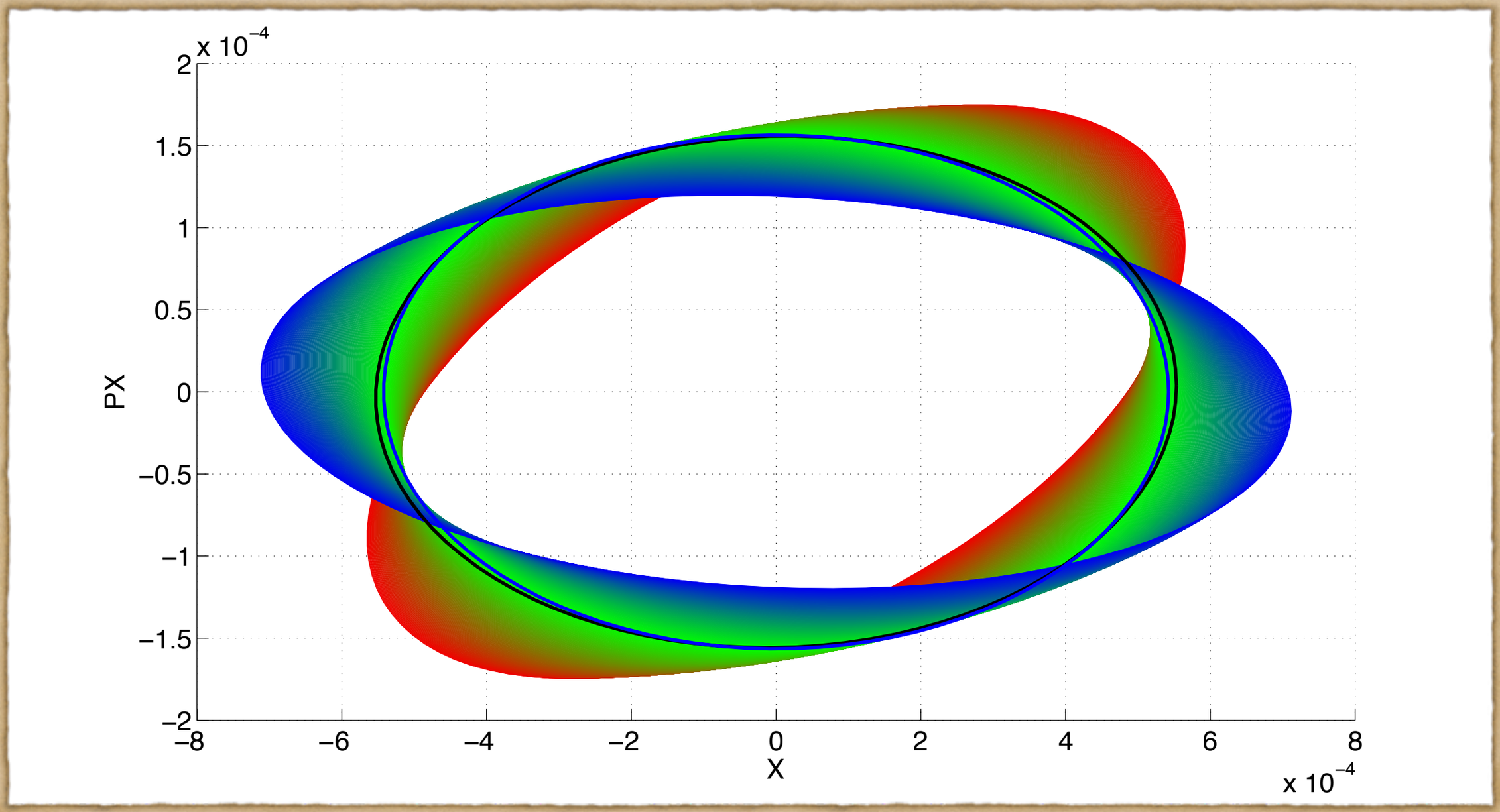
- Followings plots based on PT-simulation

Final ellipses: only chromatic effects

One can easily assume that dispersion is constantly zero for each energy

-> No displacements in phase space of the ellipse center.

- Chromatic effects seems to be negligible for our energy spread (assumed 0.6 % sigma)

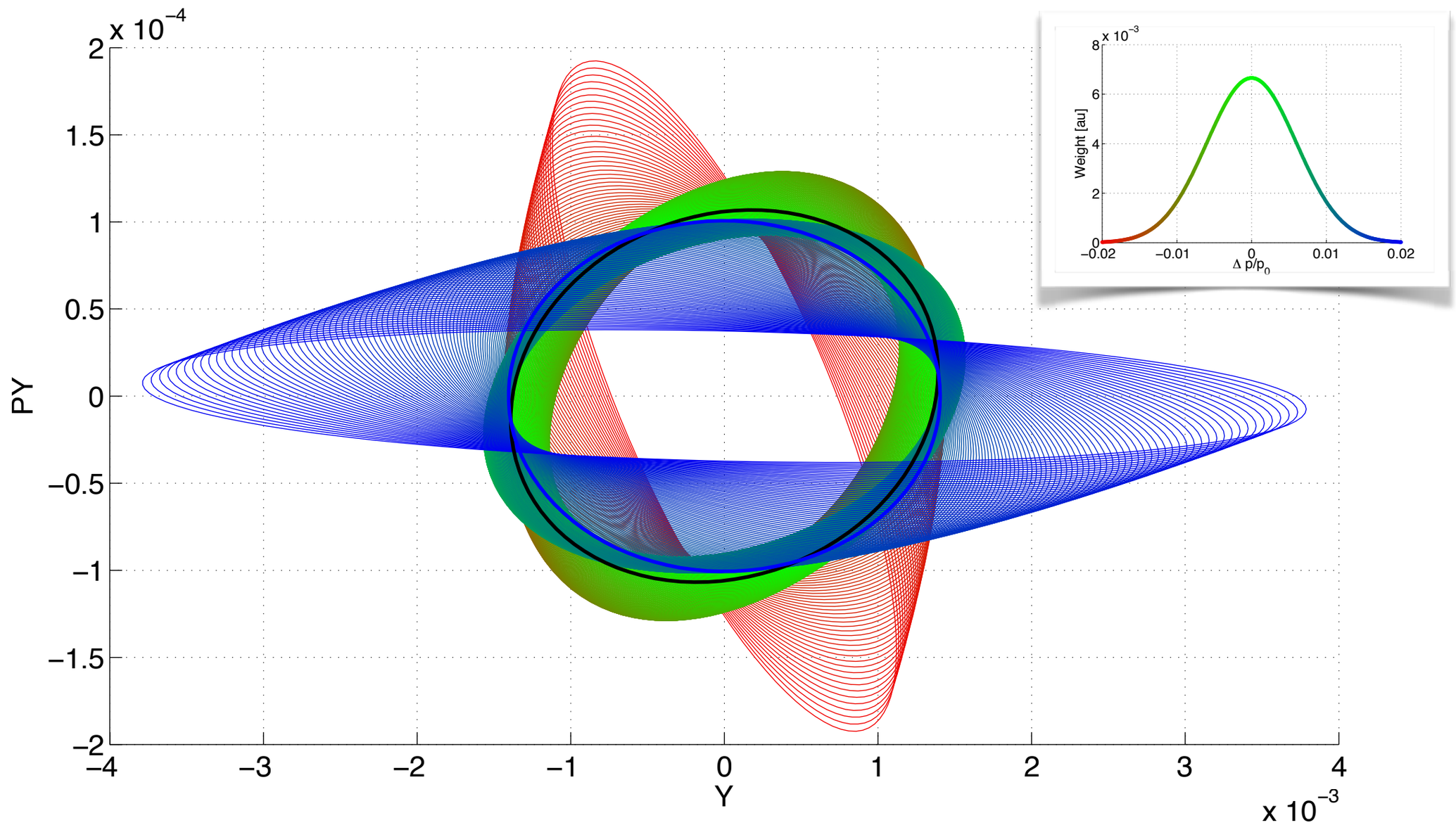


davide.gamba@cern.ch

Final ellipses: Y-PY plane

Big chromatic effects in the vertical plane

- Still this effects looks to be negligible for our energy spread (assumed 0.6 % sigma)

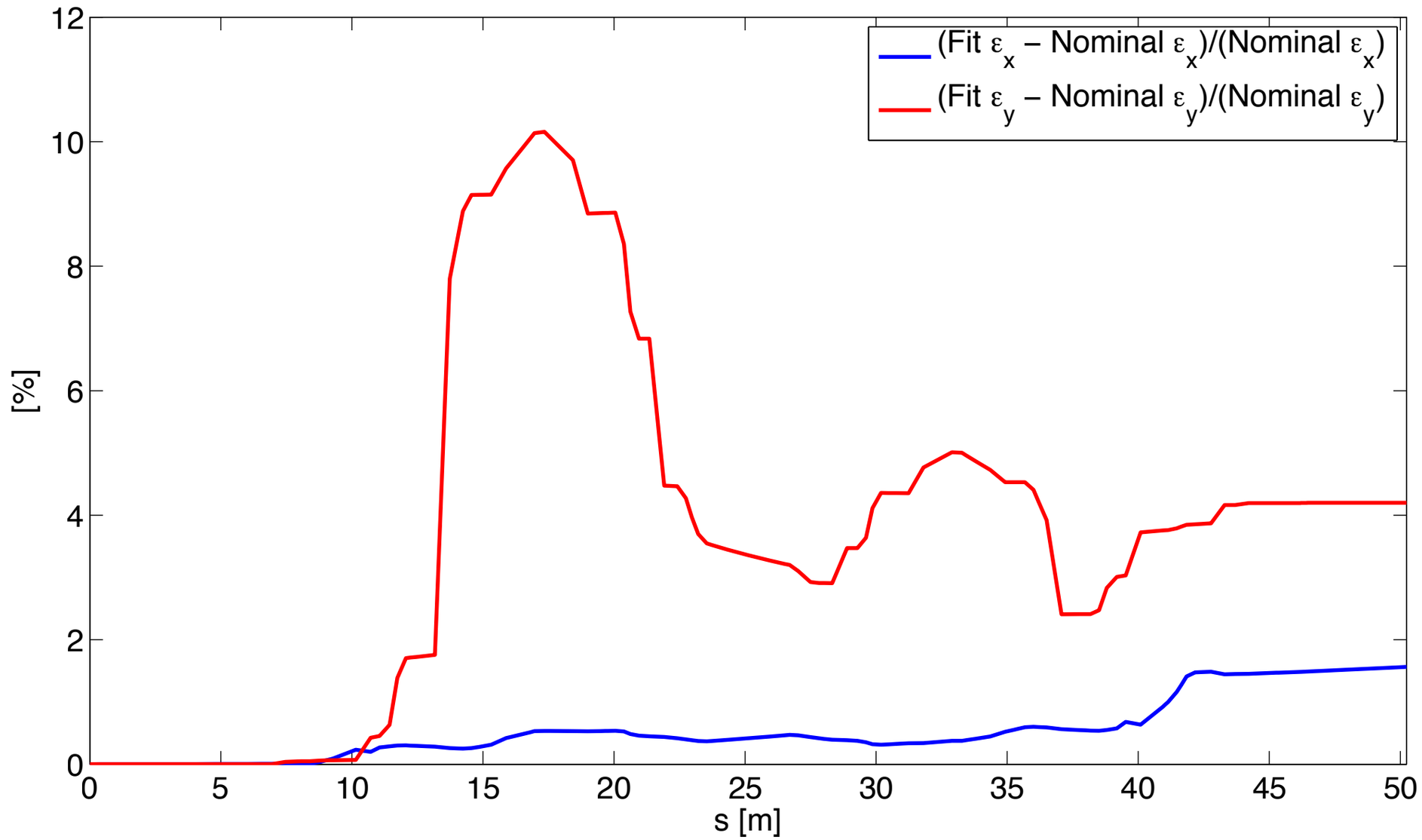


davide.gamba@cern.ch

Ellipses along the machine: only chromatic effects

Without generating any particle one can easily calculate the projected emittance all along the beam line.

- Here only chromatic effects are assumed both in horizontal and vertical.

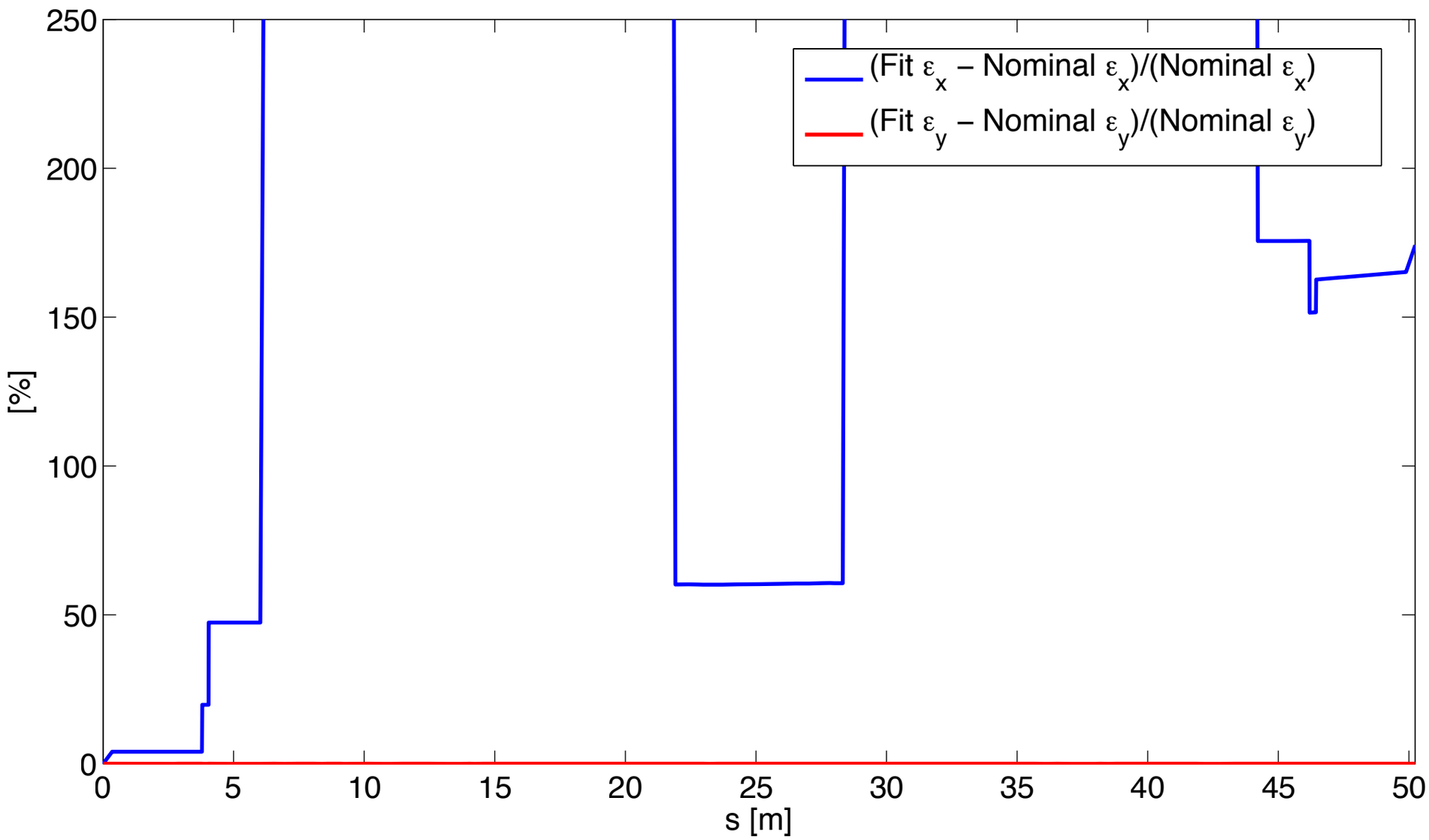


davide.gamba@cern.ch

Ellipses along the machine: only dispersion effects

Similar, but always considering the "nominal ellipse" all along the machine for all the energies.

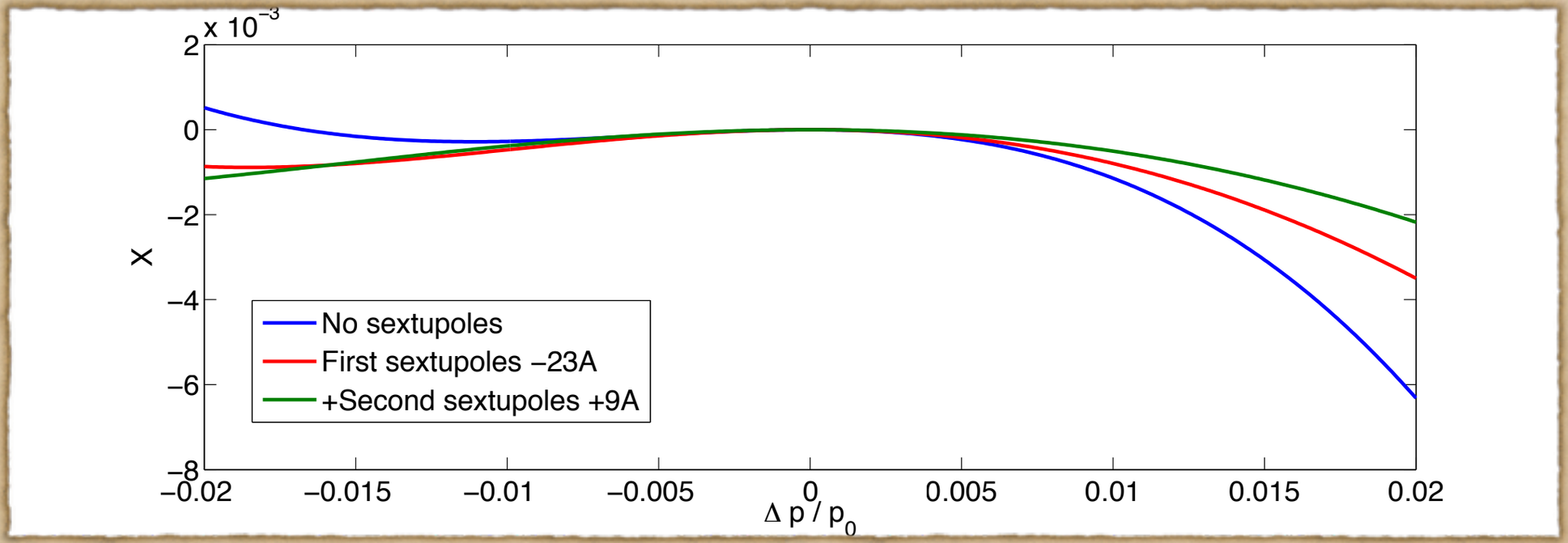
- Since there is no coupling between the planes, no effect in vertical plane in this case.

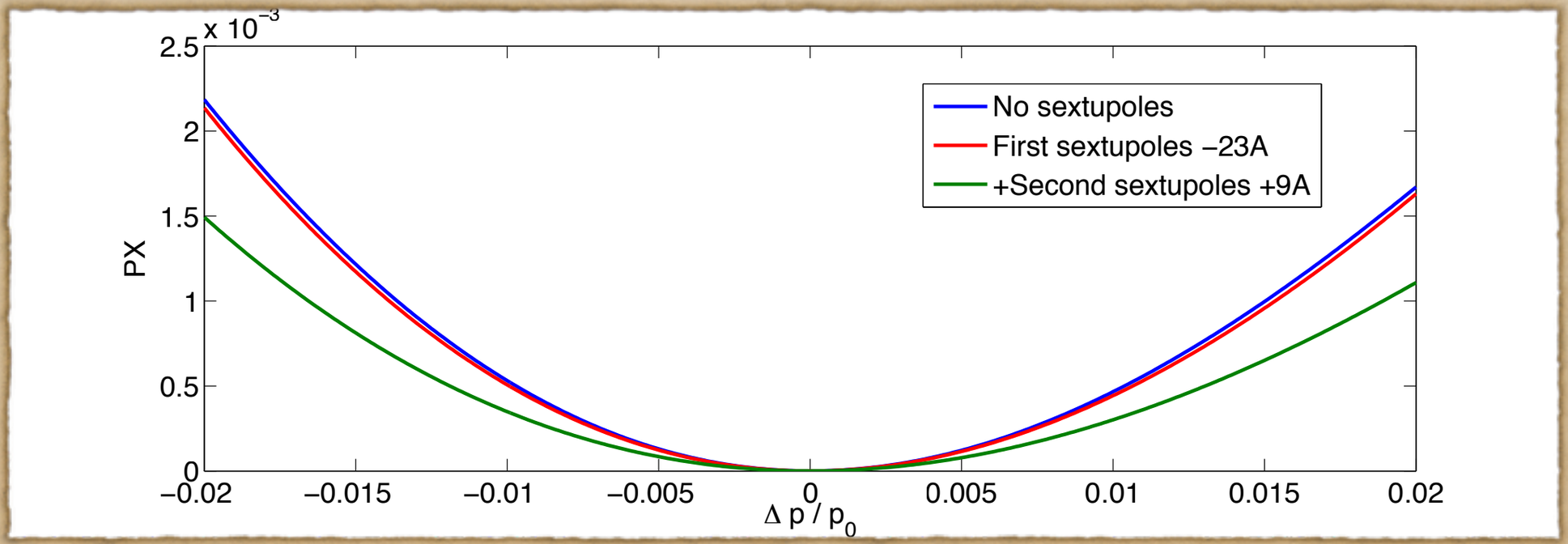


davide.gamba@cern.ch

Experimental test: sextupolar dispersion correction

- Simulated end of DL X/PX as a function of DELTAP (actually using PT simulation!)

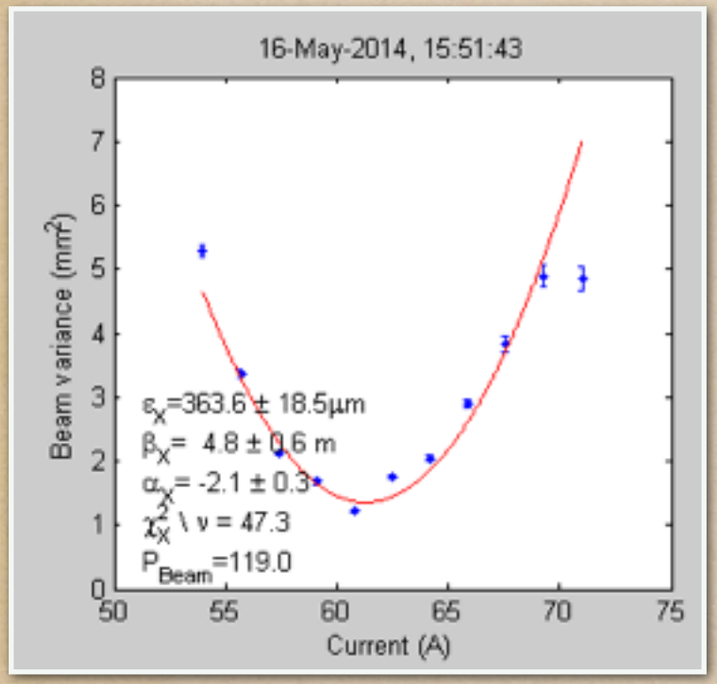




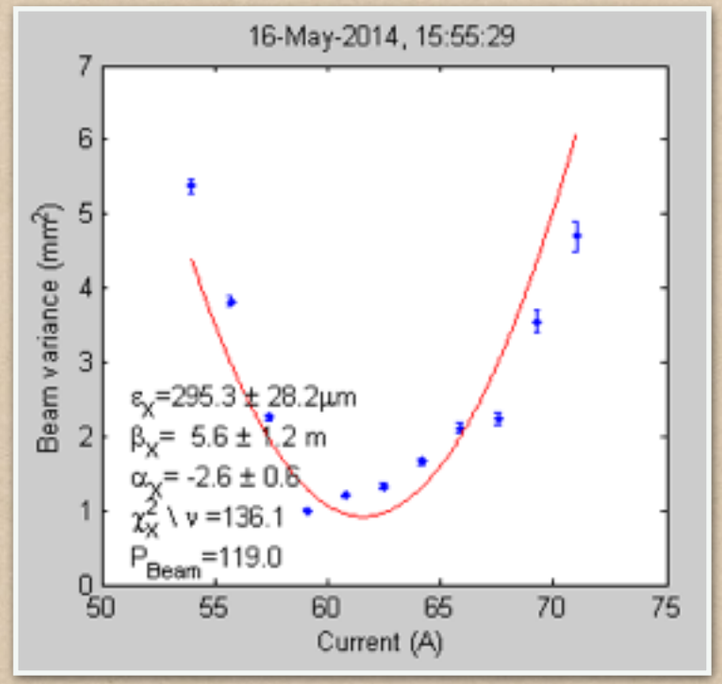
davide.gamba@cern.ch

Experimental results

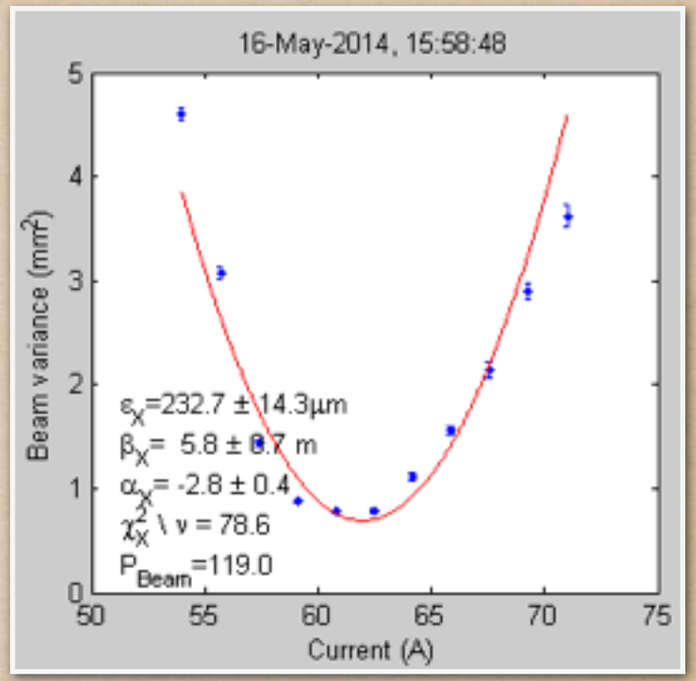
- Implementing sextupolar correction of second-order dispersion.
- Measuring emittance in downstream measurement line at different stages.



No sextupoles on.



First family at -23 A



First family at -23 A
Second family at +9 A

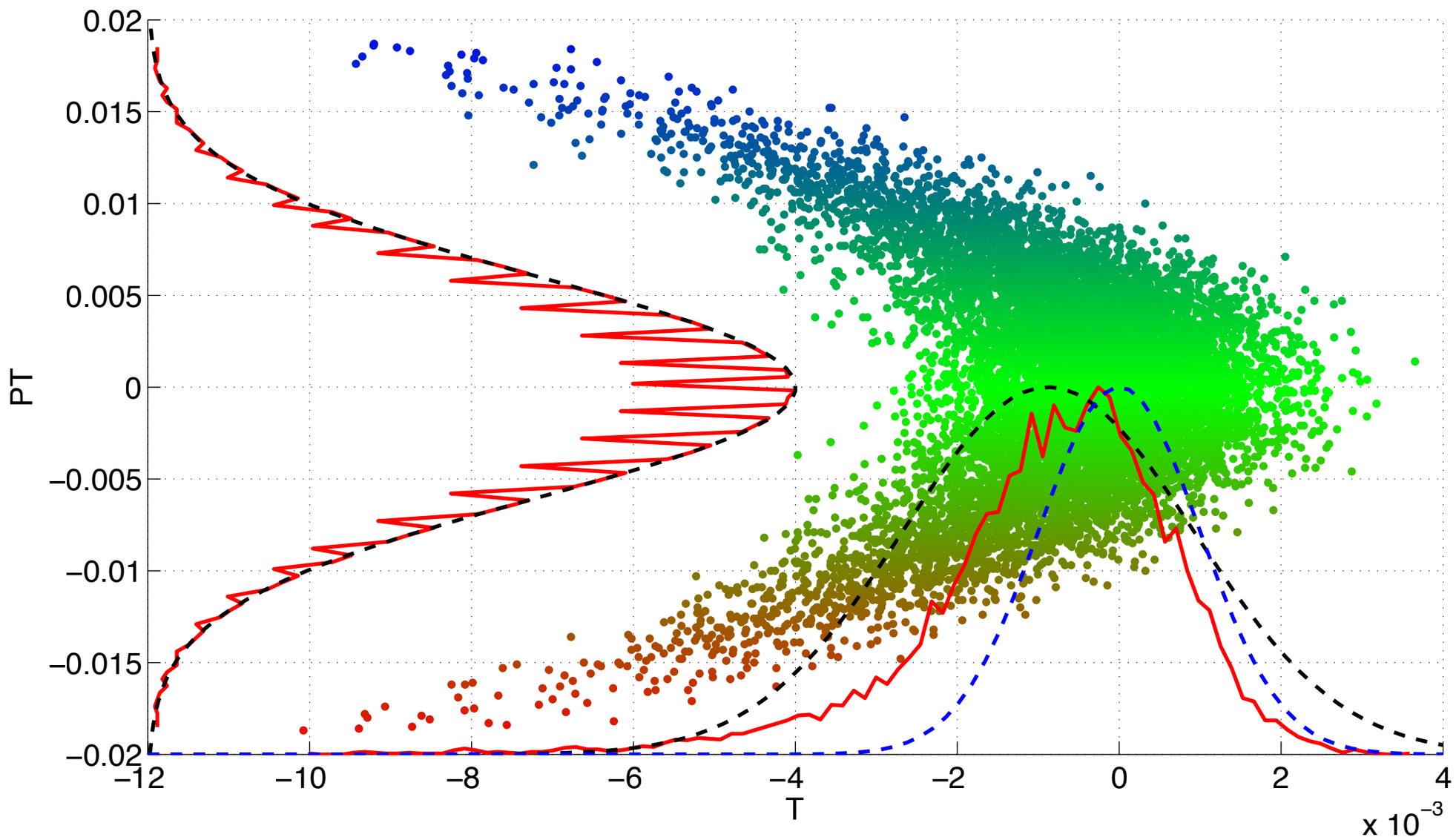
Thanks to P. Skowronski and T. Persson

davide.gamba@cern.ch

T-PT plane after one turn in DL

Same method (scanning PT values), same matrices, just looking at different plane.

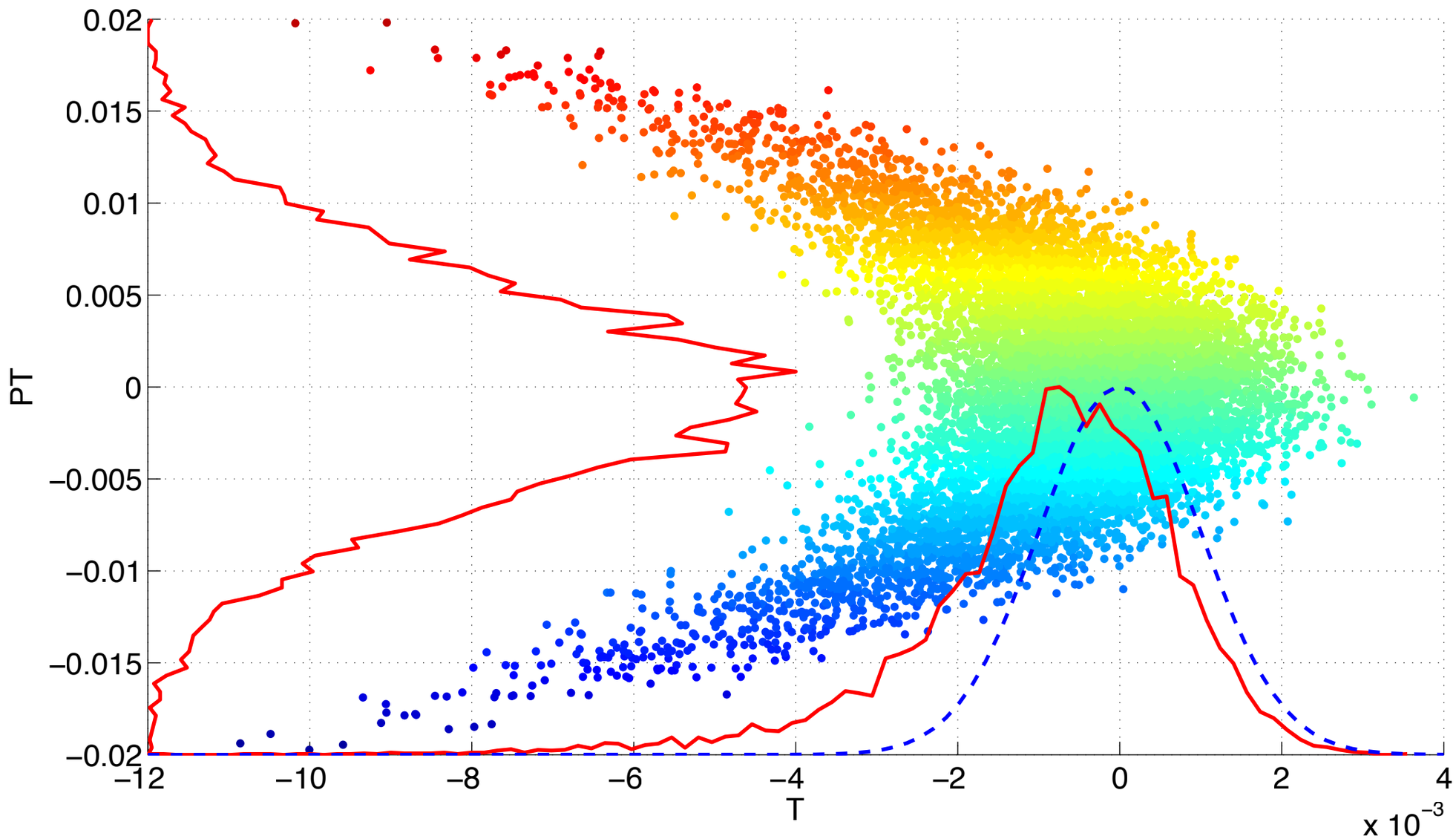
- PT clearly is what we set.
- Long tail on T projection compared to ideal case (blue) assuming initial 1 mm σ.



davide.gamba@cern.ch

T-PT plane - PTC-TRACK

Same initial conditions, similar consistent results (blue is nominal bunch length, 1mm σ).



davide.gamba@cern.ch

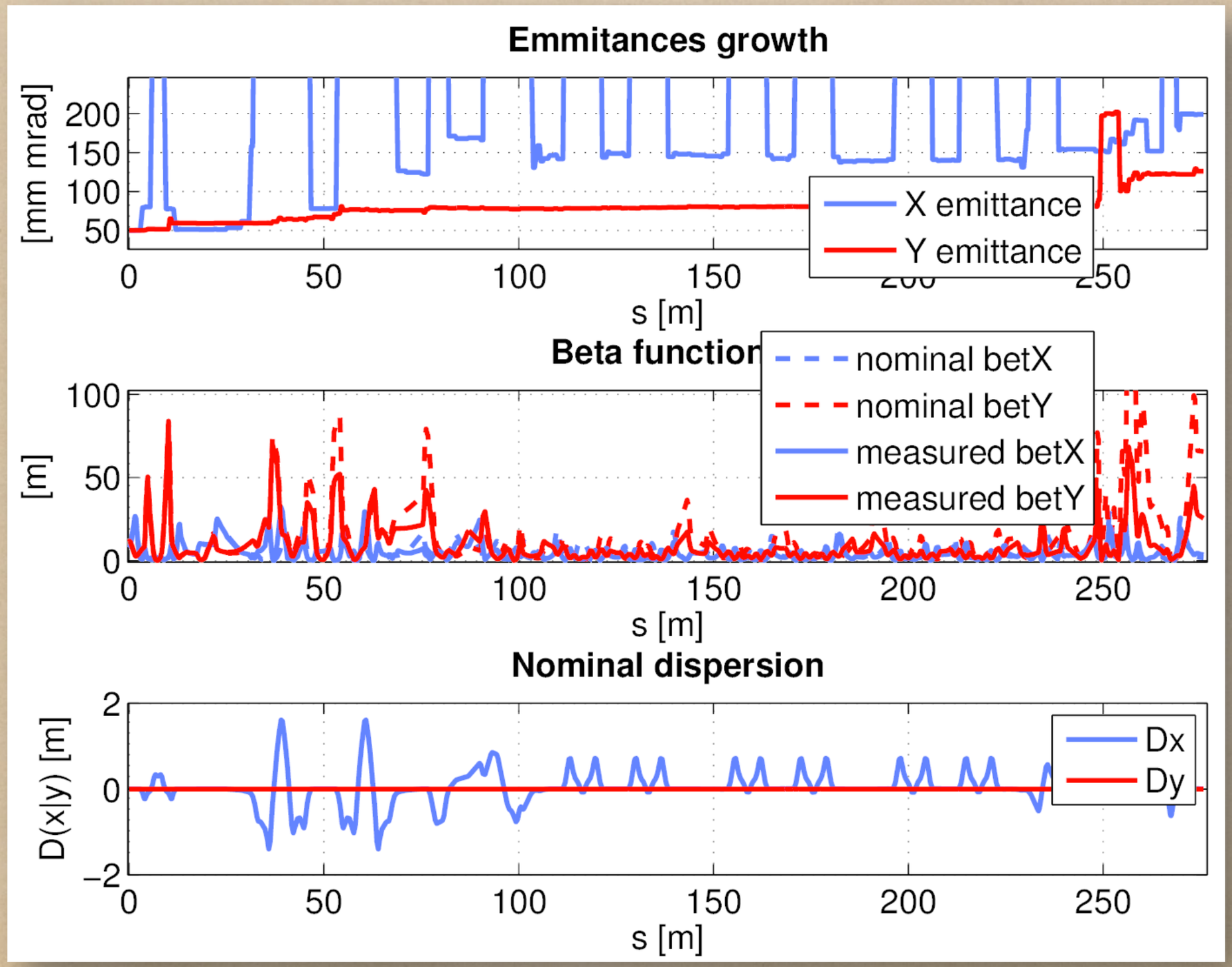
Summary

- Simple method to study energy-related non linearities.
  - Still need to verify that is giving reasonable results.
  - A strategy to compute a reasonable beam size needed.
- In CTF3 current Delay Loop it looks like there is a strong non-linear effect on horizontal dispersion:
  - Emittance can easily double.
  - Tails becomes big: difficult to transport them.
- Sextupolar correction seems to help:
  - Promising experimental results.
  - Difficult to apply in CTF3 due to misalignments.
- On the longitudinal plane looks like there is a even bigger effect.

Thank you for your attention

davide.gamba@cern.ch

An old example for the whole DBRC (single passage)



davide.gamba@cern.ch